Published as: Ergonomics 2016, 59:8 1026-1037
Available from: M.J.Griffin@soton.ac.uk

Transmission of vibration through gloves: effects of material thickness

Khairil Anas Md Rezali[†] and Michael J. Griffin

Human Factors Research Unit, Institute of Sound and Vibration Research, University of Southampton, SO17 1BJ. United Kingdom

kamr2g11@soton.ac.uk, M.J.Griffin@soton.ac.uk

[†]Now at: Department of Mechanical and Manufacturing Engineering, Universiti Putra Malaysia, 43400 Serdang Selangor, Malaysia.

Corresponding author:
Michael J. Griffin,
Human Factors Research Unit,
Institute of Sound and Vibration Research,
University of Southampton,
Highfield,
Southampton, SO17 1BJ,
United Kingdom.
Telephone: +44 (0)23 8059 2277
Email: M.J.Griffin@soton.ac.uk

Abstract

It might be assumed that increasing the thickness of a glove would reduce the vibration transmitted to the hand. Three material samples from an anti-vibration glove were stacked to produce three thicknesses: 6.4, 12.8, and 19.2 mm. The dynamic stiffnesses of all three thicknesses, the apparent mass at the palm and the finger, and the transmission of vibration to the palm and finger were measured. At frequencies from 20 to 350 Hz, the material reduced vibration at the palm but increased vibration at the finger. Increased thickness reduced vibration at the palm but increased vibration at the finger. The measured transmissibilities could be predicted from the material dynamic stiffness and the apparent mass of the palm and finger. Reducing the dynamic stiffness of glove material may increase or decrease the transmission of vibration, depending on the material, the frequency of vibration, and the location of measurement (palm or finger).

Keywords: Anti-vibration gloves, biodynamics, transmissibility, impedance, hands, fingers

Practitioner summary

Transmission of vibration through gloves depends on the dynamic response of the hand and the dynamic stiffness of glove material, which depends on material thickness. Measuring the transmission of vibration through gloves to the palm of the hand gives a misleading indication of the transmission of vibration to the fingers.

1. INTRODUCTION

The use of powered vibratory hand tools is associated with the development of the hand-arm vibration syndrome in tool operators (Griffin and Bovenzi, 2002). This syndrome includes dysregulation in the peripheral vascular response to cold (i.e., vibration-induced white finger) and disorders in the sense of touch (e.g., tingling and numbness in the fingers).

Gloves have been investigated as a means of controlling the risks associated with the hand-arm vibration syndrome. In some countries a glove must conform to the requirements of International Standard ISO 10819 (2013) before it can be sold as an 'anti-vibration glove'. The standard specifies how to measure the transmission of vibration from a cylindrical handle to the palm of the hand, but has major limitations (Griffin, 1998). Indeed, a glove that conforms to the standard is not necessarily beneficial (e.g., McDowell *et al.*, 2013) and a glove that fails the standard might be beneficial. One of the limitations is that there is no standardised method of measuring the transmission of vibration to the fingers, even though the principal disorders caused by hand-transmitted vibration are observed in the fingers. For research purposes, the transmission of vibration through gloves has been estimated from their effects on vibration transmitted to the knuckle (Wu and Griffin, 1989; Paddan and Griffin, 1999), the fingernail (Paddan and Griffin, 1999), and the dorsal surfaces of the fingers (Welcome *et al.*, 2014). The transmission of vibration from powered tools through gloves to the hand has also been measured (Pinto *et al.*, 2001; Dong *et al.*, 2013).

The transmission of vibration through a dynamic system (e.g., vibration isolator) depends on the dynamic loading on the system (e.g., mechanical impedance or apparent mass of the device supported by the isolator), so the transmissibility of a glove depends on the apparent mass of the hand in contact with the glove and not only on the dynamic properties of the glove. However, there is little understanding of factors likely to affect glove transmissibility (e.g., the effects of variations in the impedance of the hand when operating different tools and the effects of variations in glove dynamic stiffness). It is difficult to quantify glove dynamic stiffness and hand impedance in conditions similar to those when handling a powered tool and, in any event, factors such contact area, contact force and arm posture vary within and between tools and tool operators.

The biodynamic responses of the hand depend on the frequency of the vibration (e.g., Miwa, 1964a) and the direction of the vibration (e.g., Reynolds, 1977). The apparent mass of the hand is high at lower frequencies but decreases considerably as the frequency of vibration increases (Reynolds, 1977; O'Boyle and Griffin, 2004; Xu *et al.*, 2011). The resonance frequency in the apparent mass of the hand depends on the part of the hand contacting a vibrating surface. At frequencies less than about 50 Hz the apparent mass at the fingers is considerably less than the apparent mass at the palm (Concettoni and Griffin, 2009). The transmission of vibration through a material to the fingers will therefore differ from the transmission of vibration through the same material to the palm of the hand, because the dynamic properties of the fingers differ from the dynamic properties of the hand.

The dynamic properties of the material used in a glove affect the transmissibility through the material to the palm of the hand (e.g., O' Boyle and Griffin, 2004, Laszlo and Griffin, 2011). When optimising the transmission characteristics of a glove, some control over the dynamic properties of the material is required, but this is difficult because the prediction of the dynamic properties from the physical and chemical characteristics of glove material is not usually possible. A variable that can be expected to alter the dynamic properties, and that may be changed easily, is the material thickness. Such changes should have predictable effects of the dynamic properties. International Standard 10819:2013 suggests the thickness of the glove material at the fingers should be equal to, or greater than, 0.58 times the thickness of material in the palm, but there are no reported studies of the effect of material thickness on the transmissibility of gloves to either the palm of the hand or to the fingers.

The objective this study was to measure the transmission of vibration to the palm of the hand and to the tip of the index finger with a resilient material having three different thicknesses. The apparent mass at the palm and at the finger, and the dynamic stiffnesses of the material, was also measured. It was hypothesised that the thickness of the material would alter both the dynamic stiffness and the transmissibility of the glove material, and that the measured transmissibility could be predicted from the measured apparent mass of the hand or finger and the measured dynamic stiffness of the material.

2. METHODS

2.1 *Glove materials*

Three samples of foam material were cut from a glove classed as an anti-vibration glove according to ISO 10819:1996. All samples were 25-mm in diameter with an uncompressed thickness of 6.4 mm and weight of 0.34 grams. The samples were stacked together to produce three thicknesses: 6.4 mm, 12.8 mm, or 19.2 mm.

2.2 *Subjects*

Fourteen male subjects participated in the study: median age 27 years (range 23 to 33), stature 171 cm (165 – 196), weight 65 kg (40 – 110), hand circumference 200 mm (192 – 255), and hand length 200 mm (180 – 220).

The experiment was approved by the Ethics Committee of the Faculty of Engineering and the Environment at the University of Southampton.

2.3 *Measuring the apparent mass of the hand*

An accelerometer (B&K 4371) was secured to an aluminium plate attached to the table of a vibrator (Derritron VP4) orientated so as to produce vertical vibration. A force transducer (Kulite TC2000 500) with a 25-mm diameter input plate secured at the top was attached to the aluminium plate. The force transducer was used to measure the dynamic response of the hand during vibration exposure (Figure 1). An oscilloscope provided feedback to subjects so that they could monitor the force applied to the plate (Figure 2).

FIGURE 1 ABOUT HERE

An accelerometer (B&K 8307) installed in a 25-mm diameter wooden adapter (weighing 5.06 grams including accelerometer) was placed on top of the input plate. This miniature accelerometer measured vibration at the hand interface.

The subjects sat with their arms not otherwise supported and placed the palm of their hand, or the tip of their index finger, on the wooden adapter and pushed down with a force of 10 N. Random vibration (10 s over the frequency range 5 to 500 Hz at 3.24 ms^{-2} r.m.s., frequency-weighted with W_h according to ISO 5349-1:2001) was generated using MATLAB (R2011b) and *HVLab* toolbox (version 1.0). The vibration spectrum was produced by combining a flat constant bandwidth acceleration spectrum (with an unweighted magnitude of 12 ms^{-2} r.m.s.) with a flat constant bandwidth velocity spectrum (having an unweighted magnitude of 15 ms^{-2} r.m.s.), with both spectra band-pass filtered at 5 and 500 Hz.

FIGURE 2 ABOUT HERE

2.4 *Measuring the transmissibility of the glove material to the hand and finger*

The material samples were placed on the 25-mm diameter input plate secured to the top of the force transducer to measure the transmissibility of the material to the palm or to the index finger. The 25-mm diameter wooden adapter was placed on top of the material, with the palm or tip of the index finger placed on the wooden adapter exerting a downward force of 10 N. Other conditions of the test were the same as when measuring the apparent mass of the hand and the finger. The order of measuring the material transmissibilities and the apparent mass of the hand was randomised. Each subject underwent one exposure in each condition after training for about 5 minutes before the experiment commenced.

2.5 *Measuring the dynamic stiffnesses of the materials*

An ‘indenter rig’ (Figure 3) was used to determine the dynamic stiffness of the glove material. A force transducer with 25-mm diameter plate was attached to a bearing located at the upper part of the rig. Another 25-mm diameter plate was secured to the vibrator platform. The samples of glove material were placed between the two 25-mm plates. The materials were subjected to a preload force of 10 N by turning the preload screw. An accelerometer was attached to the lower plate to measure the input vibration generated by the vibrator (Derritron VP4 vibrator). A 10-s period of random vertical vibration (5 to 500 Hz) was generated using MATLAB (R2011b) and *HVLab* toolbox (version 1.0). The vibration was presented at a magnitude of 3.5 ms^{-2} r.m.s. (weighted using W_h according to ISO 5349-1:2001). The acceleration spectrum used to measure material dynamic stiffness differed from that used to measure apparent mass so as to obtain measurable forces over the range 20 to 300 Hz.

FIGURE 3 ABOUT HERE

2.6 ***Analysis***

Constant bandwidth frequency analysis was performed across the frequency range 20 to 350 Hz with a frequency resolution of 2 Hz and 84 degrees of freedom.

2.6.1 Transmissibility of the glove material to the hand and finger

The material transfer function, $T(f)$, was determined from the ratio of the cross-spectral density of the input and output acceleration, $A_{io}(f)$, to the power spectral density of the input acceleration, $A_{ii}(f)$:

$$T(f) = A_{io}(f)/A_{ii}(f) \tag{1}$$

The coherency, $\gamma^2(f)$, was calculated using:

$$\gamma^2{}_{io}(f) = \frac{\left|A_{io}(f)\right|^2}{A_{ii}(f)\,A_{oo}(f)} \tag{2}$$

where $A_{oo}(f)$ is the power spectral density of the output acceleration.

2.6.2 Apparent mass of the hand and finger

The apparent mass at the palm or the index finger, $M_h(f)$, was determined from the ratio of the cross-spectral density of the acceleration and force, $F_{io}(f)$, to the power spectral density of the input acceleration, $G_{ii}(f)$:

$$M_h(f) = F_{io}(f)/G_{ii}(f) \tag{3}$$

The coherency, $\gamma^2(f)$, was calculated using:

$$\gamma^2{}_{io}(f) = \frac{\left|F_{io}(f)\right|^2}{G_{ii}(f)\,F_{oo}(f)} \tag{4}$$

where $F_{oo}(f)$ is the power spectral density of the force.

When measuring the apparent mass, the masses of the force transducer, the 25-mm diameter metal plate, and the 25-mm diameter wooden adapter all contributed to the measured dynamic force (Figure 1). The influence of this force was subtracted from the total force using mass cancellation in the frequency domain. The mass to be cancelled was determined using the method in Section 2.3, so as to measure the dynamic force and the acceleration without either the hand or the finger. It was assumed that the apparent mass of the hand or finger, M_h(f), was given by:

Apparent mass of the hand or finger, $M_{\mathrm{h}}(f) = M_{\mathrm{T}}(f) - M_{\mathrm{s}}(f)$ (4)

2.6.3 where $M_T(f)$ is the apparent mass of the hand or finger including the mass of the moving system, and $M_s(f)$ is the apparent mass of the moving system other than the hand or finger. All values are complex quantities.

2.6.4 Dynamic stiffness of the material

The dynamic stiffness of the material, $S(f)$, was determined from the ratio of the cross-spectral density of the input acceleration and the output force, $F_{mio}(f)$, to the power spectral density of the input displacement $-\omega^{-2}A_{mii}(f)$:

$$S(f) = F_{mio}(f)/(-\omega^{-2}(A_{mii}(f))) \quad (5)$$

where $F_{mio}(f)$ is the dynamic force transmitted by the material, $A_{mii}(f)$ is the input acceleration, and ω is the angular frequency (ω = 2πf). Based on the Kelvin Voigt model, the dynamic stiffness of the material can also be represented by $S(f) = k + ic\omega$, where k is the equivalent stiffness of the material and c is the viscous damping of the material.

2.7 *Impedance model for predicting material transmissibility to the hand and finger*

The impedance model used to calculate the transmissibility of the glove material to the palm of the hand and to the index finger is shown in Figure 4.

FIGURE 4 ABOUT HERE

During the measurement of the glove material transmissibility, the apparent mass of the hand or the finger and the dynamic stiffness of the material are:

Apparent mass of the hand = $M_h(f) = F_h(f)/A_h(f)$ (6)

Dynamic stiffness of material = $S(f) = F_h(f)/(\omega^{-2}(A_h(f) - A_i(f)))$ (7)

where F_h (f) is the force applied to the hand, $A_h(f)$ is the acceleration at the hand, $A_i(f)$ is the acceleration measured at the input plate, and $\omega^{-2}(A_h(f) - A_i(f))$ is the relative displacement of the material.

Equations 6 and 7 can be expressed in terms of the force transmitted by the material to the hand:

$$M_h(f)\,A_h(f) = \omega^2\; S(f)\,(A_h(f) - A_i(f)) \tag{8}$$

Thus, the predicted transmissibility of the material to the hand or finger is:

$$\frac{A_h(f)}{A_i(f)} = \frac{\omega^{-2} S(f)}{\omega^{-2} S(f) - M_h(f)} = T_h(f) \tag{9}$$

The apparent mass of the hand, $M_h(f)$ was calculated with mass cancellation (as explained in Section 2.6.2). For the calculation of the predicted transmissibilities, the mass of the wooden adapter was not included in the mass cancellation. The wooden adapter with accelerometer had a mass of 5.06 g that added to the apparent mass of the hand or finger and would have influenced the transmissibility of the material, especially the finger that had a lower apparent mass.

3. RESULTS

3.1 *Dynamic stiffness and viscous damping of the glove material*

The stiffness and damping of the glove material decreased as the material thickness increased (Figure 5). The viscous damping of the material was high at lower frequencies but decreased as the frequency of vibration increased.

FIGURE 5 ABOUT HERE

3.2 *Apparent mass at the palm and the index finger*

Inter-subject variability in the apparent mass at the palm and at the index finger is shown in Figure 6. The median apparent masses at the palm and at the index finger of the subjects were high at lower frequencies but decreased considerably with increasing frequency of vibration. At all frequencies, the apparent mass at the palm was greater than the apparent mass at the index finger (Figure 6).

FIGURE 6 ABOUT HERE

3.3 *Transmissibility of the glove material to the palm of the hand and to the finger*

Inter-subject variability in the transmissibility of the glove material to the palm and to the index finger is shown for each material thickness in Figure 7. Some subjects showed two resonances while most showed only one resonance.

FIGURE 7 ABOUT HERE

The median transmissibility of the glove material to the palm of the hand varied according to the material thickness (Figure 8, left). One resonance frequency, between 30 and 40 Hz, decreased as the thickness of the material increased. The glove material attenuated vibration at frequencies greater than about 40 Hz, with the attenuation increasing with increasing material thickness.

FIGURE 8 ABOUT HERE

The median transmissibility of the glove material to the index finger shows the material appreciably amplified vibration at lower frequencies but attenuated the vibration at higher frequencies. The first resonance frequency in the transmissibility of the glove material to the finger reduced from about 166 Hz with a thickness of 6.4 mm to about 100 Hz with a thickness of 19.2 mm (Figure 8, right).

3.4 *Predicted transmissibility of the glove material to the palm and to the index finger*

The predicted transmissibilities varied between subjects, because they depend on the apparent mass at the palm and at the finger which differs between people (Equation 6). Predictions of the glove material transmissibility are shown for all subjects and all three thickness of the glove material at the index finger in Figure 9. The individual predicted transmissibilities of the glove material are generally similar to the individual measured transmissibilities.

FIGURE 9 ABOUT HERE

Notwithstanding the individual variability, with all three material thicknesses, the median predicted transmissibility to the palm of the hand and to the index finger was similar to the median measured transmissibility over the range 20 Hz to 350 Hz (Figure 10). The greatest percentage difference between the median measured and the median predicted transmissibility was 28%, which occurred with 19.2-mm thickness at the palm at 350 Hz, although not visible in Figure 10 because the transmissibility is very low (around 0.081) at this frequency.

FIGURE 10 ABOUT HERE

4. DISCUSSION

4.1 *Apparent mass at the palm and at the finger*

At all frequencies of vibration, the palm of the hand had greater apparent mass than the index finger (Figure 6). However, the relative difference between the apparent masses at both locations decreased as the frequency of vibration increased. This is consistent with the apparent mass at higher frequencies at both locations being controlled by the soft tissues, whereas at lower frequencies the apparent mass is more dependent on the mass of the upper limb, as suggested by Reynolds and Angevine (1977) and Dong *et al.* (2005).

The apparent masses at the palm and at the index finger measured in this study have been compared with those reported previously (Figure 11). The apparent mass of the hand reported by Dong *et al.* (2005) and Xu *et al.* (2011) is greater than the apparent mass found here, possibly because they measured the apparent mass with a vertical palm pushing horizontally and with a greater surface of the hand in contact with the input plate or handle. The apparent mass of a full-hand will be greater than the apparent mass measured with a 25-mm diameter contactor, as in this study.

FIGURE 11 ABOUT HERE

The apparent mass at the palm measured in this study is similar to the apparent mass at the palm reported by O'Boyle and Griffin (2004), who measured with similar conditions (i.e., size of contact area, contact force, hand posture, the palm of the hand, vertical vibration) but with different subjects.

4.2 *Transmissibility of the glove material to the palm and to the index finger*

The transmissibility to the palm was considerably less than the transmissibility to the index finger at all frequencies from 20 to 350 Hz, when the comparison is made with the same material thickness (Figure 8). With the thinnest material, the median transmissibility to the palm was around unity at frequencies less than 50 Hz. At higher frequencies, and at all frequencies with the two thicker materials, there was attenuation in the transmission of vibration to the palm.

The frequency of the resonance in the transmissibility to the finger occurred at a higher frequency than the resonance to the palm and is similar to that found in previous studies (e.g., Paddan and Griffin, 1999; Welcome *et al.*, 2014). The resonance frequency in the transmissibility to the finger was at a higher frequency than the resonance in the transmissibility to the palm of the hand. This resulted in the glove material amplifying the transmission of vibration to the finger at all frequencies up to 272 Hz with the thinnest material, and at all frequencies up to 140 Hz with the thickest material.

The greater transmissibility of the glove material to the finger than to the palm of the hand has been reported previously (Paddan and Griffin, 1999). The difference is large and casts doubt on the value of a standardised glove test that does not yield understanding of the influence of a glove on the transmission of vibration to the fingers (Griffin, 1998). The findings of this study suggest that measuring the transmission of vibration to the palm of the hand is not sufficient to assess the value of an ‘anti-vibration’ glove.

4.3 *Effects of dynamic stiffness of glove material*

The dynamic stiffnesses of the material varied with the thickness of the material. If the material behaved linearly, it would be expected that as the thickness doubled the stiffness would halve and the damping would halve. Although this makes assumptions that will not be valid for all materials, the measured stiffness and the measured damping were approximately half when the thickness doubled from 6.4 to 12.8 mm (Figure 5)

The reduction in dynamic stiffness with increase in material thickness affected the transmission of vibration to the palm of the hand and to the index finger (Figure 8). At frequencies lower than about 100 Hz, the transmissibility to the palm of the hand decreased as the thickness of the material increased whilst the transmissibility to the finger increased with increasing material thickness.

The same trends reported in this paper were found when performing the same measurements with three thicknesses of a gel material taken from a glove that did not pass the test for an anti-vibration glove in ISO 10819 (1996) (Figure 12). The gel material attenuated the vibration transmitted to the palm of the hand but amplified the transmission of vibration to the index finger (except for the higher frequencies with the thicker material). The resonance frequency in the transmissibilities to the index finger decreased as the thickness of the material decreased. Similar to the foam glove material, whereas the transmissibility of the gel material to the palm tended to reduce with increasing thickness, the transmissibility to the index finger increased with increasing thickness at frequencies less than about 200 Hz.

FIGURE 12 ABOUT HERE

Reducing the dynamic stiffness of the material in a glove can reduce the transmission of vibration to the palm of the hand but increase the transmission of vibration to the fingers at some frequencies. The requirement in ISO 10819:2013 for an anti-vibration glove to have the part covering the fingers the same properties as the part covering the palm, and with a thickness equal to, or greater than, 0.55 times the thickness at the palm needs reconsideration.

4.4 *Inter-subject variability in the measured and predicted material transmissibility*

Across the 14 subjects, inter-subject variability in transmissibilities to the palm of the hand was less than for the index finger (Figure 7). The large variability in transmissibility to the finger is similar to the findings of Paddan and Griffin (1999). The variability may have primarily arisen from differences in the mechanical impedance of the fingers, but also from small difference in the preload force influencing the dynamic stiffness of the material (e.g., O'Boyle and Griffin, 2004). There can also be large inter-subject variability in the measures obtained using the method of assessing whether a glove can be classed as an anti-vibration glove in ISO10819:1996 and ISO 10819:2013 (e.g., O'Boyle and Griffin, 2001; Laszlo and Griffin, 2011).

4.5 *Predicted transmissibility of the glove material to the palm and to the index finger*

The predicted and the measured transmissibilities show good agreement for individual subjects as well as in the median data, notwithstanding differences in apparent mass between subjects and between the palm and the finger. This suggests it might be possible to predict the benefits of wearing a particular glove for an individual worker.

The use of an adapter to measure vibration within a glove according to ISO 10819 (1996) and ISO 10819 (2013) may result in underestimation or overestimation of the transmissibility of a glove (Paddan and Griffin, 2001; Dong *et al*., 2005). From the measures obtained in this study, it was possible to estimate the transmissibility of the material without the wooden adapter, by predicting the transmissibility with and without the mass of the wooden adapter included in the mass cancellation (see Section 3.6.2). The wooden adapter had little effect on the predicted transmissibility to the palm of the hand, but the transmissibility to the index finger was slightly affected (Figure 13). This is consistent with the finding of Mann and Griffin (1996) and Dong *et al.* (2005). It is to be expected that the effect of the adapter on the transmissibility will increase with increasing frequency of vibration, because the apparent mass of the index finger reduces with increasing frequencies whereas the apparent mass of the adapter is the same at all frequencies.

FIGURE 13 ABOUT HERE

4.6 *Glove transmissibility measured in this study and in working places*

The glove material transmissibilities measured in this study may differ from those for gloves used in work with vibratory tools because the conditions may differ (different contact locations and areas of contact, different contact forces, different postures of the hand and arm). For example, so as to use the same contactor at the hand and the finger, the area of contact used in this study was smaller than implied in the ISO 10819:2013 (0.5×10^{-3} m^2 for the adapter used in this study compared with 2.0×10^{-3} m^2 in ISO 10819:2013). However, if the thickness of the material in a glove is changed, the effects on the transmission of vibration to the palm or to the fingers are likely to be consistent with the findings of this study.

The apparent mass of the whole hand is greater than the apparent mass measured at the palm in this study (Figure 11). In work with powered hand tools, the relevant apparent mass of the hand may differ from that in this study and also differ from that in the posture specified for testing gloves in ISO 10819:2013. Given that gloves are used in a wide range of conditions, the test standardised in ISO

10819:2013 will also give material transmissibilities that differ from the transmissibilities of gloves as used in some work with vibratory tools.

5. CONCLUSIONS

The difference between the apparent mass of the hand and the apparent mass of the finger has a large effect on the transmissibility of glove material to the palm and to the finger. Over much of the frequency range explored in this study (20 to 350 Hz), a glove material attenuated the transmission of vibration to the palm of the hand but amplified the transmission of vibration to the finger.

Varying the dynamic stiffness of a glove material (e.g., by changing the material thickness) can have a large effect on transmissibility to the palm of the hand and to the fingers. Reducing the dynamic stiffness may reduce transmissibility to the palm while increasing transmissibility to the finger.

The transmissibility of a glove material to the palm or a finger can be predicted from the dynamic stiffness of the material and the apparent mass measured at the palm or finger. It is also possible to predict the effect of different material properties (e.g., thickness).

The effects of gloves on the transmission of vibration to the fingers, where damage from exposure to hand-transmitted vibration is most commonly reported, will not be estimated in any useful way using the method of measuring glove transmissibility as specified in International Standard ISO 10819:2013.

6. REFERENCES

Adewusi SA, Rakheja S, Marcotte P (2010) Vibration transmissibility characteristics of the human hand–arm system under different postures, hand forces and excitation levels. Journal of Sound and Vibration 329(14): 2953-2971.

Concettoni E and Griffin MJ (2009) The apparent mass and mechanical impedance of the hand and the transmission of vibration to the fingers, hand, and arm. Journal of Sound and Vibration 325(3): 664-678.

Dong RG, Rakheja S, Mcdowell TW, Welcome DE, Wu JZ, Warren C, Barkley J, Washington B and Schopper AW (2005) A method for assessing the effectiveness of anti-vibration gloves using biodynamic responses of the hand–arm system. Journal of Sound and Vibration, 282, 1101-1118.

Dong RG., Wu JZ, McDowell TW, Welcome DE and Schopper AW (2005) Distribution of mechanical impedance at the fingers and the palm of the human hand. Journal of Biomechanical, 38, 1165-75.

Dong RG, Welcome DE, Peterson DR, Xu XS, McDowell TW, Warren C, Asaki T, Kudernatsch S, Brammer A, and Cherniack M. (2014). Tool-Specific Performance of Vibration-Reducing Gloves for Attenuating Palm-Transmitted Vibrations in Three Orthogonal Directions. International Journal of Industrial Ergonomics, 44(6), 827-839.

Griffin MJ (1990) Handbook of Human Vibration, Elsevier Academic Press ISBN: 0-12-303040-4.

Griffin MJ (1998) Evaluating the effectiveness of gloves in reducing the hazards of hand-transmitted vibration. Occupational and Environmental Medicine, 55, 340-348.

Griffin MJ and Bovenzi M (2002) The diagnosis of disorders caused by hand-transmitted vibration: Southampton Workshop 2000. International Archives of Occupational and Environmental Health, 75, (1-2), 1-5.

International Organization for Standardization (1996) Mechanical vibration and shock - Hand-arm vibration - Method for the measurement and evaluation of the vibration transmissibility of gloves at the palm of the hand. International Standard, ISO10819:1996.

International Organization for Standardization (2013) Mechanical vibration and shock - Hand-arm vibration - Method for the measurement and evaluation of the vibration transmissibility of gloves at the palm of the hand. International Standard, ISO10819:2013.

Laszlo HE and Griffin MJ (2011) The transmission of vibration through gloves: effects of push force, vibration magnitude and inter-subject variability. Ergonomics 54(5): 488-496.

Mann NAJ and Griffin MJ (1996) Effect of contact conditions on the mechanical impedance of the finger. Central European Journal of Public Health, 4, 46-49.

McDowell TW, Dong RG, Welcome DE, Xu XS, and Warren C. (2013). Vibration-Reducing Gloves: Transmissibility at the Palm of the Hand in Three Orthogonal Directions. Ergonomics, 56(12), 1823-1840.

Miwa T (1964a) Studies in hand protectors for portable vibrating tools. 1. Measurement of attenuation effect of porous elastic materials. Industrial Health 2: 95-105.

Miwa T (1964b) Studies in hand protectors for portable vibrating tools. 2. Simulations of porous elastic materials and their applications to hand protectors. Industrial Health 2: 106-123.

O'Boyle M and Griffin MJ (2001) Inter-subject variability in the measurement of the vibration transmissibility of gloves according to current standards. International Conference on Hand-Arm Vibration, 5-8 June 2001, INRS, Nancy, France.

O'Boyle M and Griffin MJ (2004) Predicting the effects of push force on the transmission of vibration through glove materials to the palm of the hand. 10th International Conference on Hand-Arm Vibration, 7-11 June 2004, Las Vegas, Nevada, USA.

Paddan GS and Griffin MJ (1999) Standard test for the vibration transmissibility of gloves. Health and Safety Executive Contract Research Report 249/1999, ISBN: 0-7176-1719-X.

Pinto I, Stacchini N, Bovenzi M, Paddan GS, Griffin MJ (2001). Protection effectiveness of anti-vibration gloves: Field evaluation and laboratory performance assessment. International Conference on Hand-Arm Vibration. N. (F).

Reynolds DD and Soedel W (1972) Dynamic response of the hand-arm system to a sinusoidal input. Journal of Sound and Vibration, 21, 339-353.

Reynolds DD and Keith RH (1977) Hand-arm vibration, Part 1: Analytical model of the vibration response characteristics of the hand. Journal of Sound and Vibration, 51(2): 237-253.

Reynolds DD and Angevine EN (1977) Hand arm vibration, Part 2: Vibration transmission characteristics of the hand and arm. Journal of Sound and Vibration, 51, 255-265.

Xu XS, Welcome DE, McDowell TW, Wu JZ, Wimer B, Warren C and Dong RG (2011) The vibration transmissibility and driving-point biodynamic response of the hand exposed to vibration normal to the palm. International Journal of Industrial Ergonomics, 41, 418-427.

Welcome DE, Dong RG, Xu XS, Warren C, and McDowell TW. (2014). The effects of vibration-reducing gloves on finger vibration. International Journal of Industrial Ergonomics, 44(1), 45-59.

Wu GL and Griffin MJ (1989) Experimental investigation of the dynamic properties of some prototype anti-vibration gloves. ISVR Technical Memorandum 693, Institute of Sound and Vibration Research, University of Southampton, SO17 1BJ, UK.

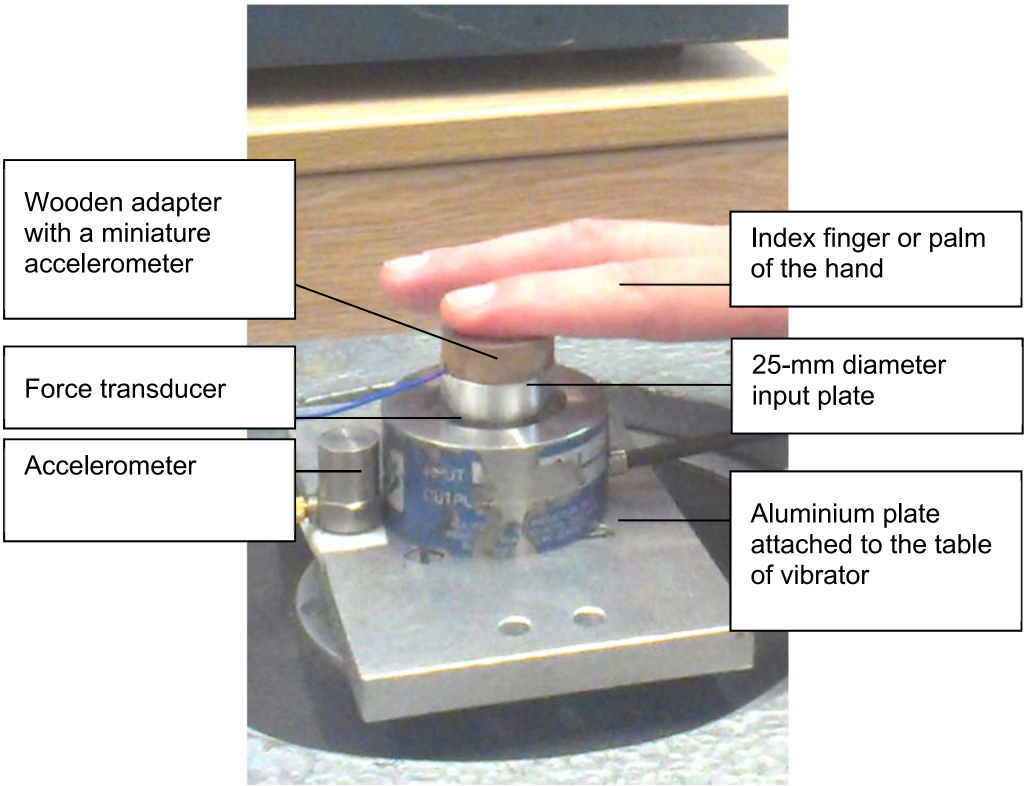

Figure 1 The arrangement for the measurement of the apparent mass of the hand and the index finger.

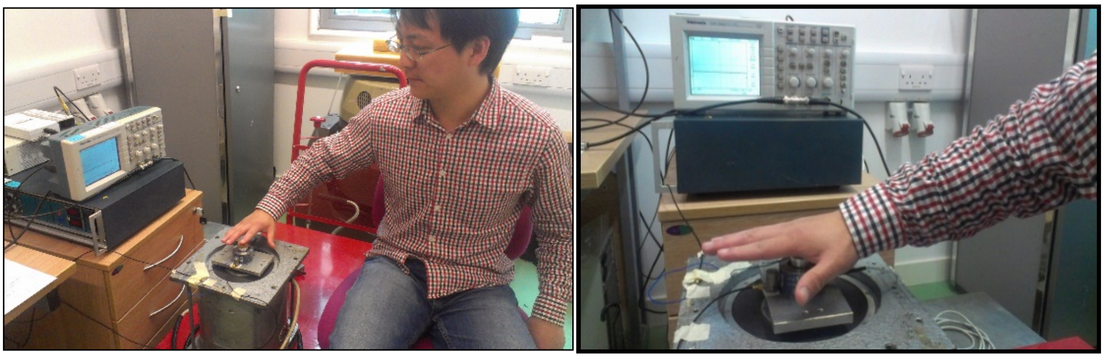

Figure 2 Left: posture of the hand for the measurement of the apparent mass at the index finger. Right: arrangement for the measurement of the apparent mass at the palm of the hand. The downward force is indicated on the oscilloscope.

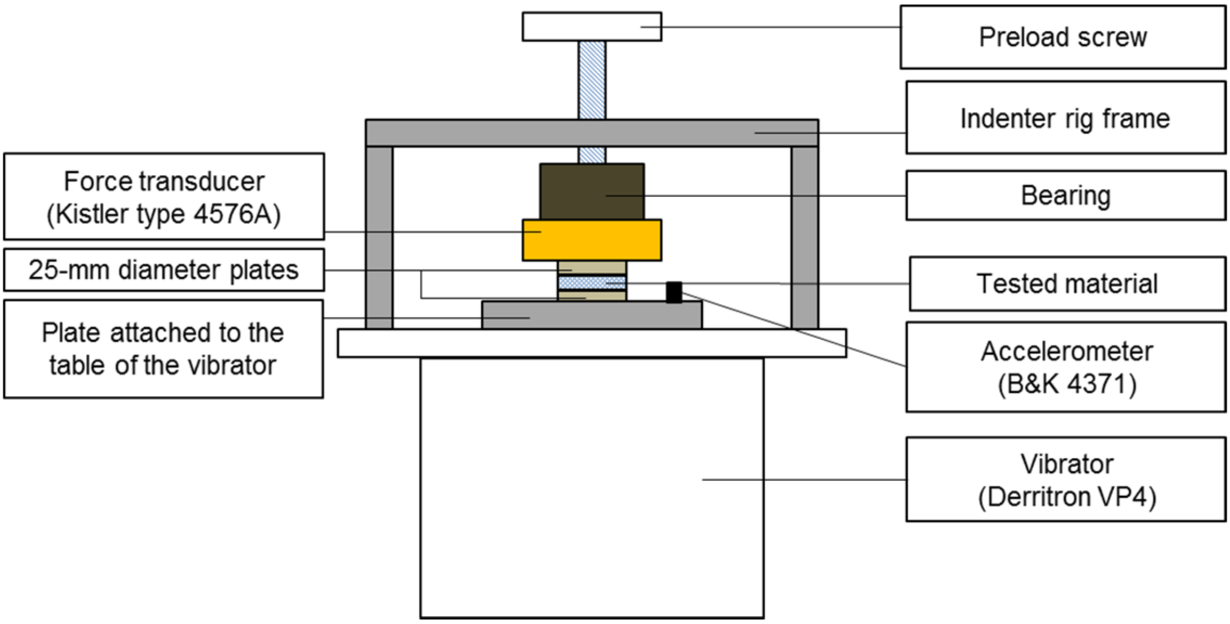

Figure 3 Diagrammatic representation of the indenter rig used to determine the dynamic stiffness of the material.

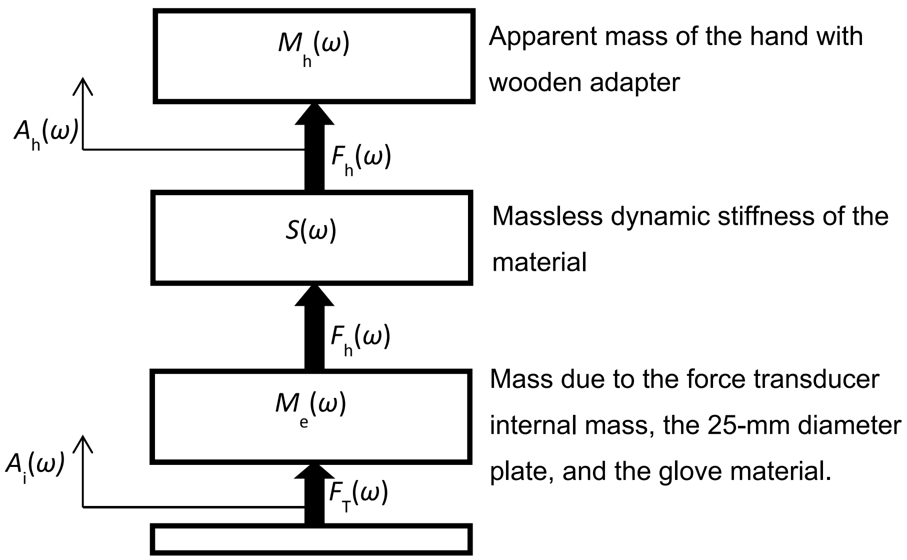

Figure 4 The impedance model of the hand and material.

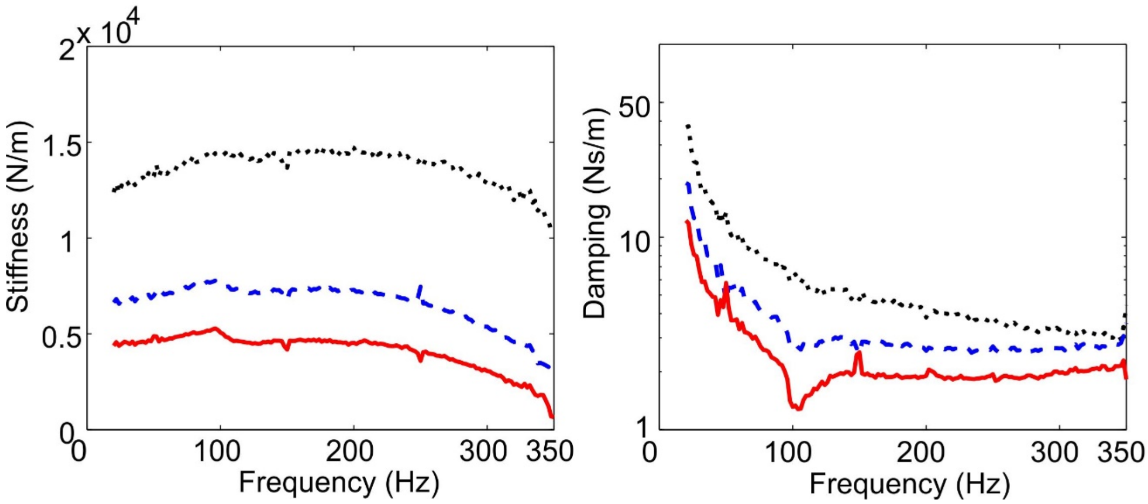

Figure 5 Dynamic stiffness of the glove material (···· 6.4 mm, - - - 12.8 mm, and — 19.2 mm).

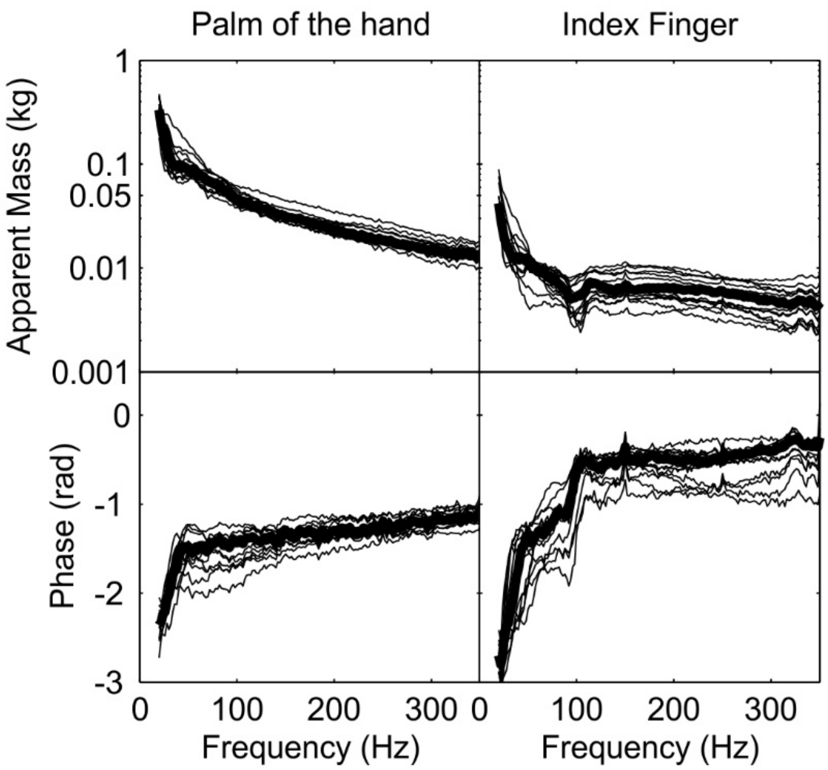

Figure 6 Apparent mass of the hand of all 14 male subjects. Left: palm; Right: index finger. (Thicker black lines: Median apparent mass).

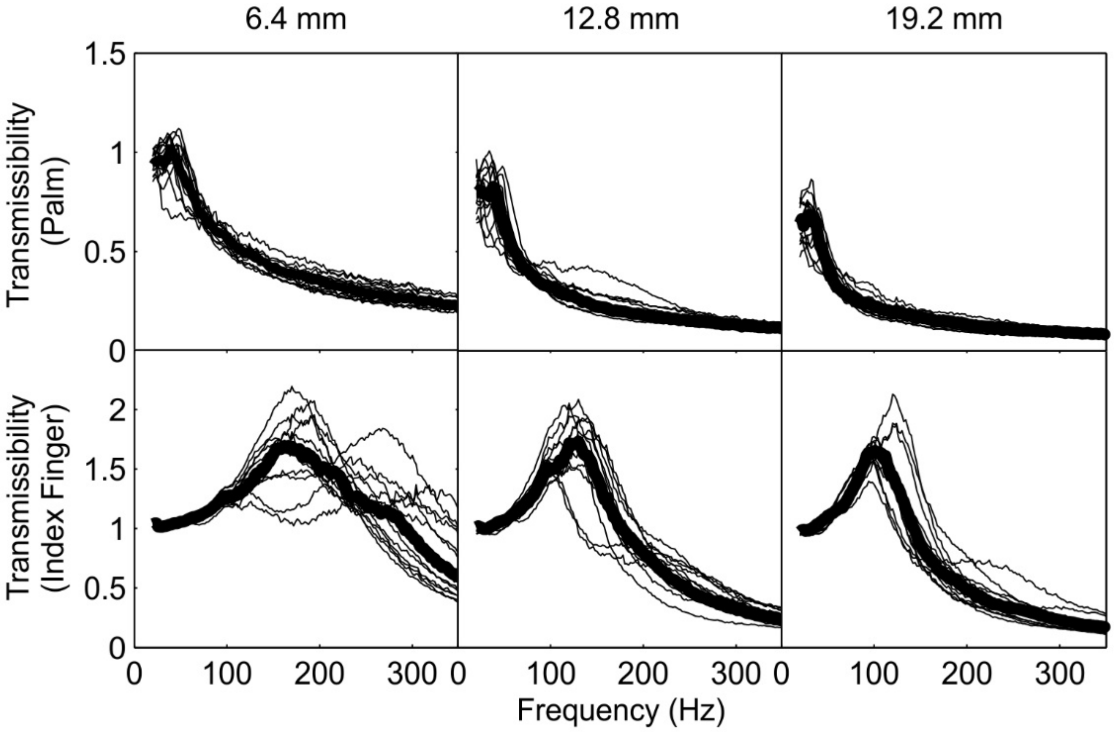

Figure 7 Transmissibility of the glove material with thickness of 6.4, 12.8, and 19.2 mm to the palm (upper graphs) and index finger (lower graphs) with 14 male subjects. Thicker lines: median transmissibility.

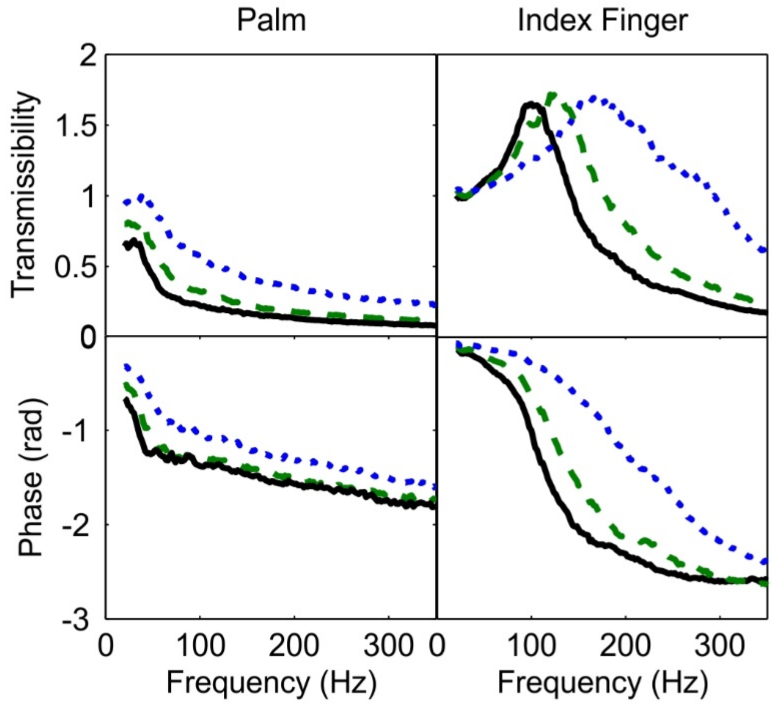

Figure 8 Median transmissibility (modulus and phase) of the glove material to the palm of the hand (left graphs) and to the index finger (right graphs) with three thicknesses of glove material: ····: 6.4 mm, ---: 12.8 mm, and —: 19.2 mm. Medians for 14 subjects.

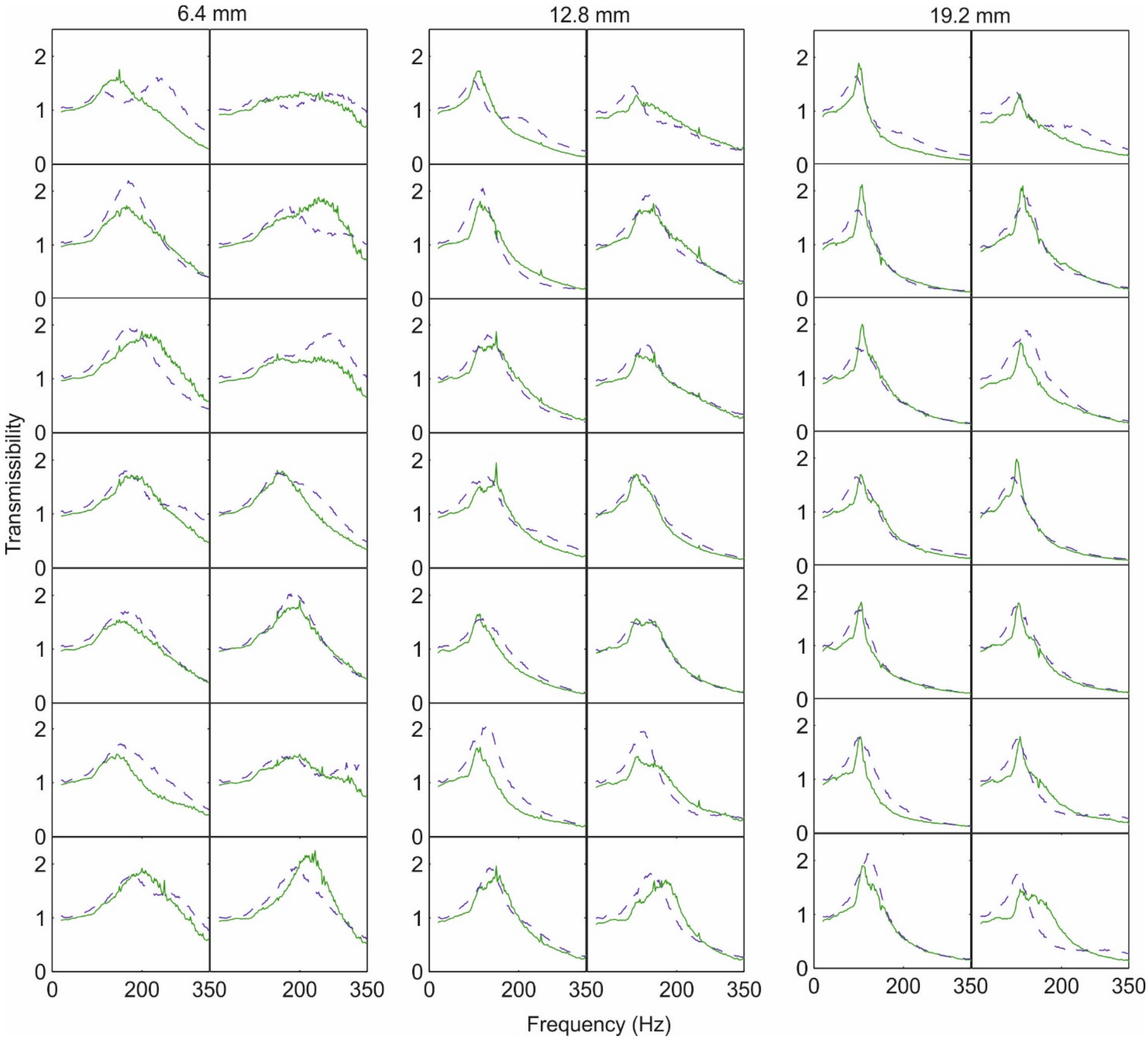

Figure 9 Predicted and measured individual transmissibility of the glove material to the index finger with material thickness of 6.4, 12.8, and 19.2 mm (---: measured, and —: predicted).

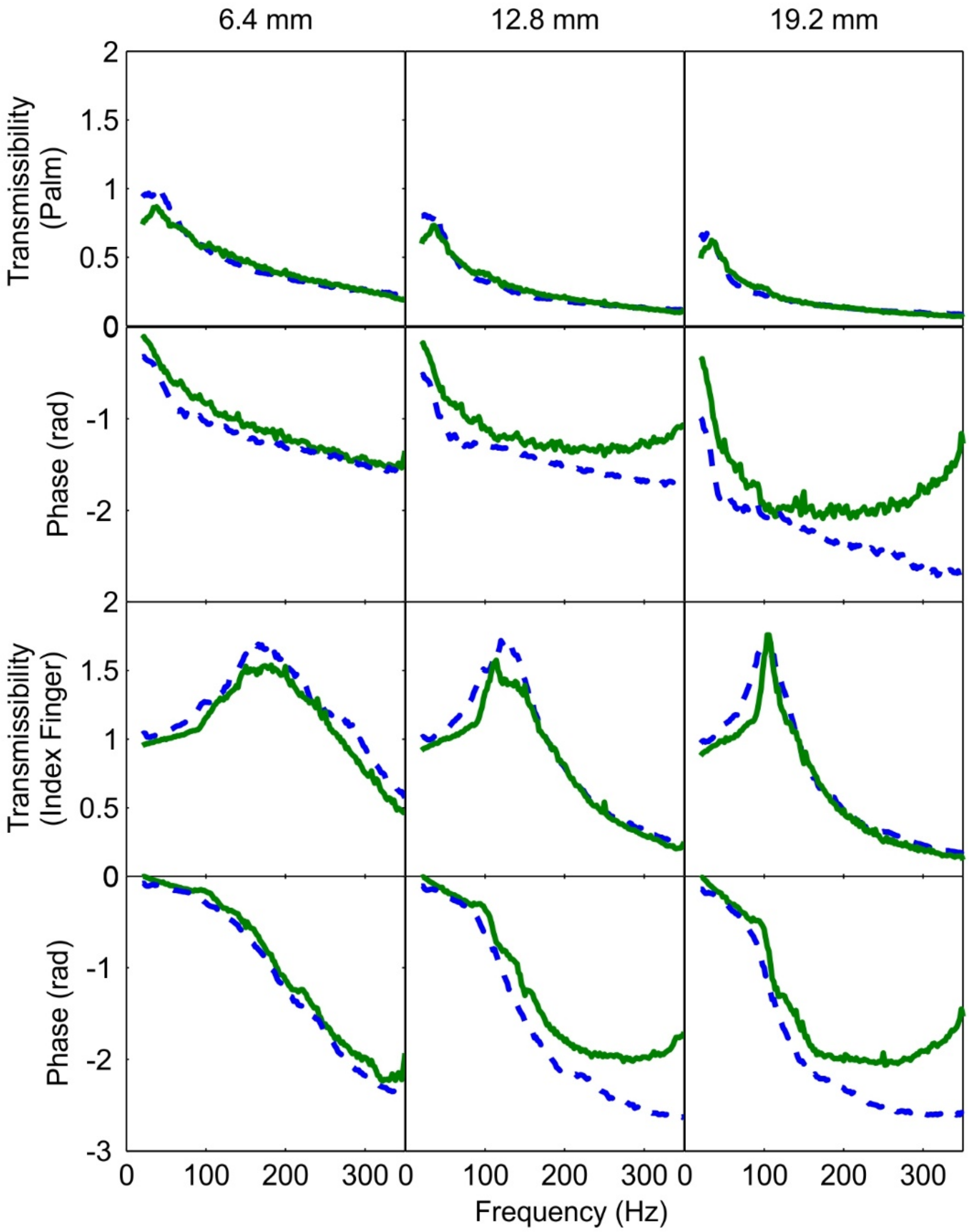

Figure 10 Predicted and measured transmissibility to the palm (upper graphs) and the index finger (lower graphs) with glove material of thickness 6.4, 12.8, and 19.2 mm (---: measured, and —: predicted). Medians for 14 subjects.

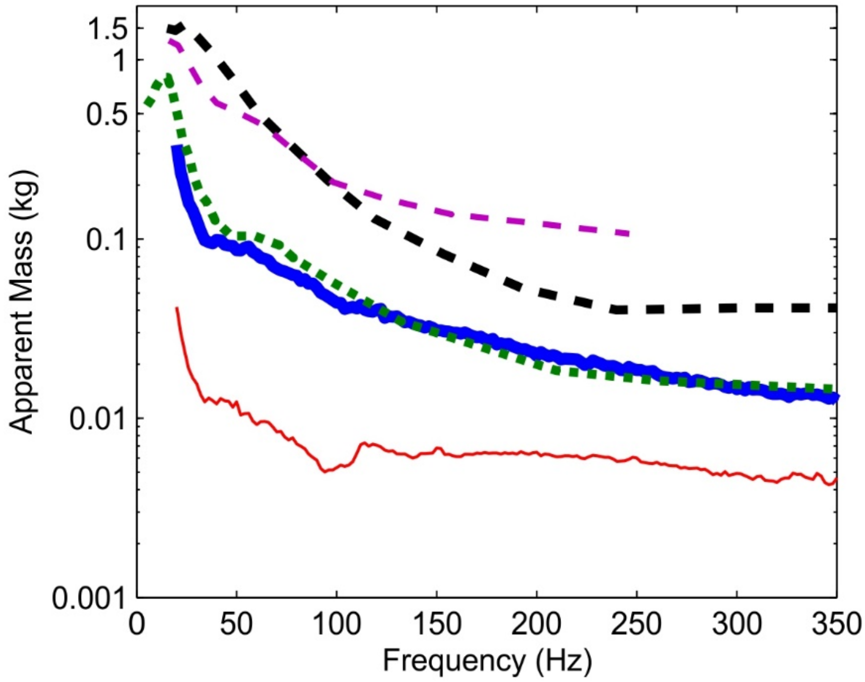

Figure 11 Apparent mass of the hand (—— palm pushing down on a flat 25-mm diameter plate at 10 N, vibration in vertical direction; —— index finger pushing down on a flat 25-mm diameter plate at 10 N, vibration in vertical direction; ▬ ▬ vertical palm pushing horizontally on a cylindrical handle with adapter at 50 N, vibration in horizontal direction (from Dong *et al.*, 2005); – – full hand pushing horizontally on a flat surface, vibration in horizontal direction (from Xu *et al.*, 2011); ▪▪▪▪▪ palm pushing down on a flat surface at 10 N on a 25-mm diameter plate, vibration in vertical direction (from O'Boyle and Griffin, 2004).

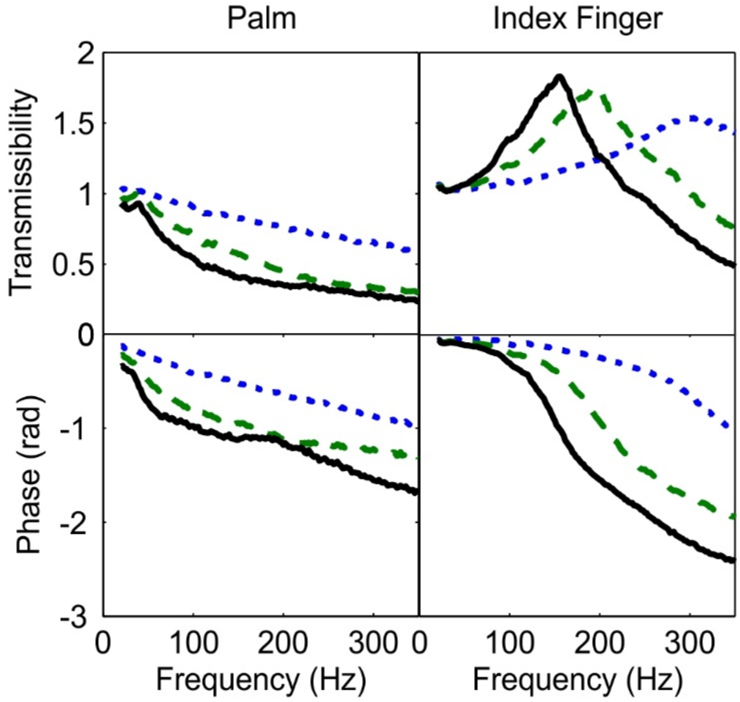

Figure 12: Transmissibility of a gel material to the palm of the hand (left graphs) and to the index finger (right graphs): ····: 6.4 mm, ---: 12.8 mm, and —: 19.2 mm. Modulus (upper graphs) and phase (lower graphs). Medians for 14 subjects.

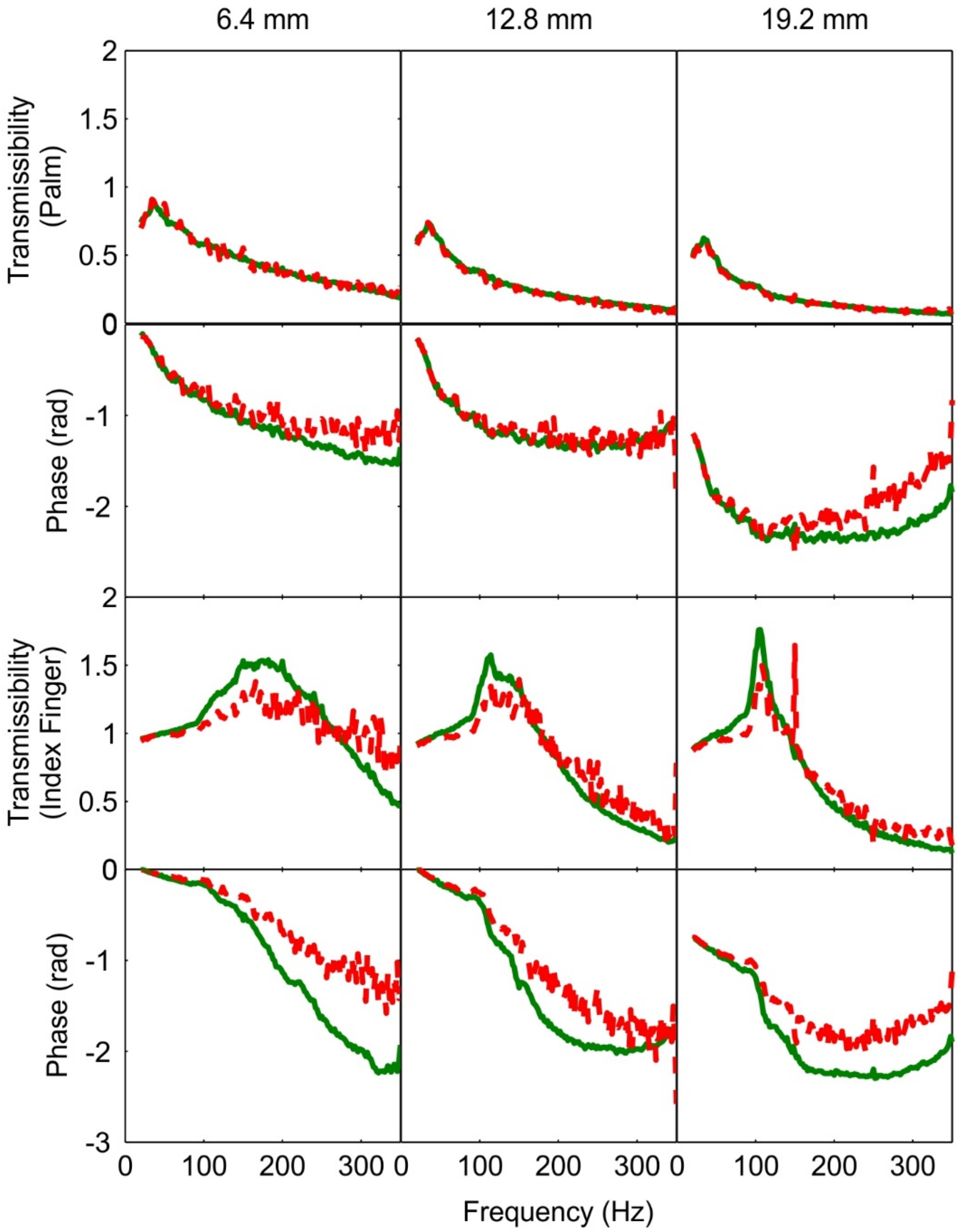

Figure 13 Comparison of predicted transmissibility to the palm (upper graphs) and to the index finger (lower graphs) with and without the wooden adapter: --- with adapter, — without adapter). Medians for 14 subjects.